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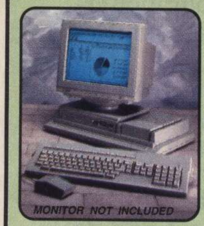

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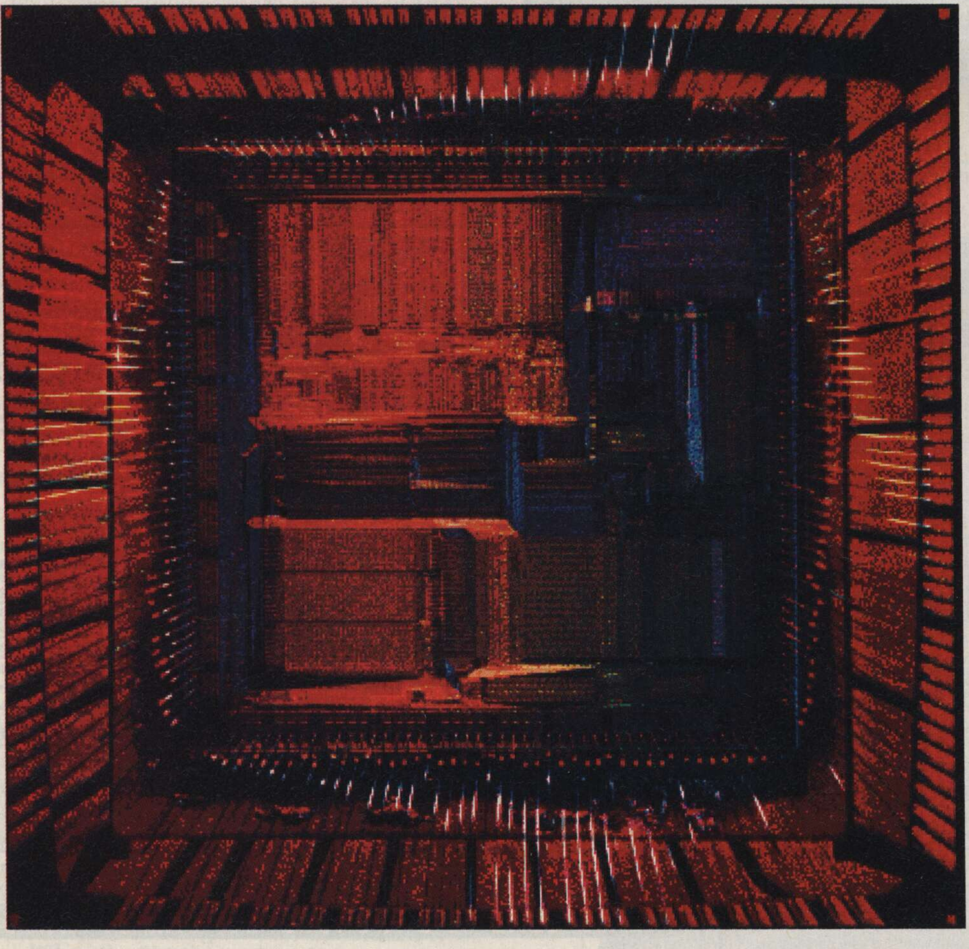
If the cap fits...

Would you be surprised to hear that Motorola's 68000 is used in far more applications than Intel's 8086 family? It's true, says Dr Alan Clements; it's certainly the microprocessor of choice in his computer architecture courses.



Less than ten years ago microprocessors were virtually invisible to the general public. There were microprocessors in point-of-sale terminals and in domestic appliances, but people never gave them a second thought. The advent of IBM's Personal Computer changed the way people look at computers. The popular journals, like *PCW* in this country and *Byte* in the US, once covered a range of 8-bit microprocessors. Now the PC is sweeping all before it and the majority of such magazines are firmly devoted to it. We will soon reach a state in which you could be forgiven for thinking that there is no alternative.

The key to the PC's success has been the standardisation of its software and hardware. Any entrepreneur can produce PC-compatible hardware that you can just plug into your PC's bus. Some PC components have become everyday words. I'm convinced that if a psychiatrist gave the word association test to a patient today, the first reaction to the word 'window' is as likely to be 'Unrecoverable Application Error' as 'cleaner'. The manufacturer of most of the microprocessors going into the PC has become so synonymous with the computer that it runs an advertising campaign based on the slogan 'Intel Inside'.

Since the PC has become a *de facto* standard, why should anyone worry about other types of computer? Well, I do, because I teach courses in computer architecture. My courses are generally based on the 68000 family and each year at least one student asks why I am not teaching the architecture of the 80386. The short answer I give is 'Just because you can't see something doesn't mean that it doesn't exist'. The long answer is provided by this article.

My job is to *teach* students, not to train them. When I teach computer architecture I present the underlying principles and expect my students to use these principles to synthesize new knowledge long after they have graduated. For example, in ten years one of my students might have to make a decision about which microprocessor to embed into an aircraft flight control system.

He or she should be able to apply the basic principles I teach in my courses. Training, by contrast, is more concerned with teaching directly applicable knowledge that enables the student to perform a specific task: a course on how to use WordPerfect would be considered as training. If I were training my students to be PC salespeople or engineers, I would certainly use the 8086 family.

I select the 68000 as a vehicle to teach computer architecture because it is much better suited to this task than members of the Intel family. Choosing the Motorola family rather than the Intel family is not a criticism of Intel's chips; indeed, I'm writing this article on a PC and not on a Macintosh based on the 68000 or 68030. Intel was responsible for the microprocessor as we know it and it wisely (from a business point of view) capitalised on its lead. Although it's a simplification, each new Intel chip is built on the foundations of its predecessor. Intel's first 16-bit chip, the 8086, was essentially an extension of the 8-bit 8080. This approach makes good economic sense because programmers can run their existing software on each new generation of Intel chips with relatively little modification.

Intel's competitor, Motorola, took a different approach to chip design. When it made the jump from an 8-bit processor (the 6800) to a 16-bit processor (the 68000), it went back to the drawing board. Unlike Intel, its new processor was in no way compatible with its old one and 8-bit users had to start again. However, by going back to the drawing board Motorola was able to produce a true 32-bit processor with consistent features. (Note that the 68000 was originally called a 16-bit processor because it communicates with memory via a 16-bit data bus. As far as the programmer is concerned, the 68000 has a 32-bit architecture because its registers are 32 bits wide.)

Before we look at what the 68000 family has to offer the teacher, we need to point out that it is not an obscure teaching tool relegated only to the classroom. The 68000 family is used in far more applications than the 8086 family. But most of the 68000's applications are invisible because they are largely used in industry or in dedicated applications (such as the laser printer). As I have said, just because you cannot see these applications it does not mean they don't exist.

Simplicity

Let's return to my job as a teacher. In a first year course I have to teach the basic principles of the central processing unit, CPU *(see page 394)*. What I need is a simple architecture — there's no point in obscuring the fundamental principles with a mass of detail. The 68000 embodies simplicity. When microprocessors were first introduced, each new chip had more instructions and addressing modes than its predecessors. Salespeople loved to emphasise this point: 'Buy my chip because it's got more instructions than brand X'. It's rather like saying 'Learn German instead of French because its nouns have three genders rather than two'.

When the 68000 was first designed, its instruction set was actually simpler than that of many 8-bit microprocessors even though it was vastly more powerful. This simplicity was achieved in two ways. Firstly, unlike the 8086 the 68000 does not have dedicated registers (the internal data storage elements which are tied to a specific task). The 68000 has eight data registers, D0 to D7, and whatever you can do to Di you can also do to Dj. So, if I tell my students that ADD XYZ,D2 is a legal instruction that adds the contents of XYZ to register D2,

What does a microprocessor do?

Probably the most miraculous aspect of the computer is its ability to achieve so much with so little. Apart from its peripherals, the computer is built out of primitive electronic elements called gates. These gates are clumped together to form more complex building blocks (the adder and the control unit). These building blocks are combined to form the central processing unit — the microprocessor. The microprocessor executes a primitive language — machine code. The human-readable version of machine code is called assembly language. All user programs are translated into machine code before they are executed.

Although the exact details of a microprocessor's operation are complex, the basic principles are simple. A program is stored in memory as a sequence of instructions. The microprocessor contains a register called a program counter that tells it the location of the next instruction in the program. When the group of bits representing an instruction is fetched from memory, gates in the processor decode the instruction and interpret it.

Conventional microprocessors operate in what is called the fetch execute cycle. During the fetch cycle an instruction is read from memory, decoded, and the program counter incremented to point to the next instruction. During the execute phase, the action of the instruction is carried out by the processor. Typical instructions have the format:

```
OPERATION   <source
    operand>,<destination operand>.
```

The source and destination operands are the locations of the data taking part in the operation. For example, MOVE D1,XYZ copies the contents of the source operand D1 (a data register inside the processor) into the memory location called XYZ.

If microprocessors could execute instructions only in a fixed sequence, they would not be able to perform all the clever operations we associate with the computer. All microprocessors are able to implement conditional behaviour and to select the next operation depending on the result of a calculation or on the value of an input. For example, the computer might read the location of the cursor on the screen and then load a program based on its position.

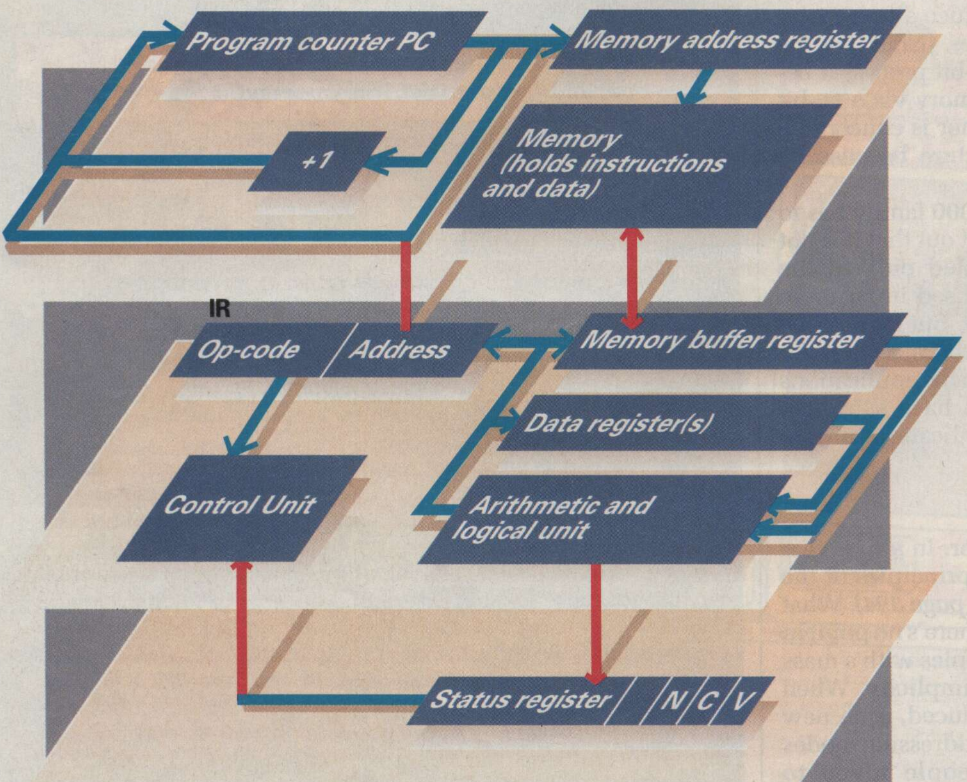
Microprocessors implement this type of behaviour by means of conditional instructions. A typical conditional instruction might have the form BPL LoadFile and means 'If the result of the last operation gave a positive result then jump to the instruction on the line with the label LoadFile, otherwise continue as normal'. The processor reads this instruction during the fetch cycle and decodes it. The logic decodes the operation BPL as branch on positive and tests the state of the processor's positive/negative bit. If the bit indicates a negative result, the instruction is concluded and the net instruction read from memory. If it indicates a positive result, the address part of the current instruction is fed to the program counter and used to replace the current value in the PC. Doing this forces a jump to a different part of the program.

A typical microprocessor executes instructions such as move A to B, add X to Y, compare P with Q, and jump to the instruction at address PQR if the last result was zero. We can translate complex languages like C++, Pascal or LISP into long sequences of machine code instructions and run them on the microprocessor. In turn, applications programs from word processors to aircraft control systems can be expressed in high level language form.

they immediately know that they can use SUB XYZ,D6 to subtract XYZ from D6. Why? Because specific registers are not dedicated to specific instructions and whatever you can do with D2 you can do with D6. Secondly, the 68000 has simplified its instruction set by giving one name to all the members of the class of instructions that transfer data from one place to another. Prior to the 68000, the programmer had to learn instructions like:

```
LDAload accumulator with data from
        memory
STAstore accumulator in memory
LDXload index register with data from
        memory
STXstore index register in memory
```

and so on. The 68000 has a simple MOVE instruction that transfers data from anywhere to anywhere. MOVE D0,D2 copies register D0 into register D2. MOVE A4,XYZ copies the contents of address register A4 into memory location XYZ. MOVE ABC,DEF copies the contents of memory location ABC into location DEF. What could be simpler? Having a powerful but simple instruction set means I can do what I'm paid to do and not waste time teaching an instruction set that is as tedious as the thirteen times table.



As the course progresses we introduce more advanced topics such as position independent code. A program may not always be located within the same region of memory. Suppose you write a device driver to control a video display. If this program accesses specific memory locations it must always be stored in the same place in every system using it. This restriction can sometimes be inconvenient, as another program might already occupy the same region of memory space. The 68000 allows you to write programs in such a fashion that the resulting binary code can be located anywhere in memory without having to be rewritten.

The trick is to avoid explicit (i.e. actual) memory addresses. For example, the 68000 instruction ADD XYZ(PC),D2 tells the processor to add the contents of the memory location that is XYZ bytes from the current instruction to register D2. It doesn't matter where you put this instruction in memory, because the data is always located XYZ bytes away. The notation XYZ(PC) is called relative addressing because the location of the data is expressed with respect to the program counter.

Students studying computer science also take courses in high level languages and in the design and construction of compilers for these languages. Two of the most important aspects of a high level language are the way in which parameters are passed between a subroutine and the program that calls it, and recursion (the ability of a subroutine to call itself). The 68000 implements, at the machine code level, powerful mechanisms that perform both these operations efficiently. For example, the 68000 has a special instruction called LINK that enables a subroutine to grab a bit of memory for its own private use. Even if an interrupt occurs and other software calls the same routine, the subroutine still carefully guards its pre-interrupt data.

In addition to learning computer languages and computer architecture, the student can be expected to study operating systems. Even here the 68000 has some interesting attributes that make it particularly suitable as a teaching machine. For example, all members of the 68000 family support a dual operating mode, not found on the 8086 family. The 68000 can operate in a supervisor mode or a user mode. When it is in its supervisor mode it runs the operating system and controls all interrupts and exceptions (software interrupts). When it is in its user mode it runs programs — applications under the control of the operating system. This apparent schizophrenia serves a useful purpose: the operating system has a higher state of privilege than the user state and users can be prevented from carrying out operations that would compromise the integrity of the system.

After the program counter, a computer's most important register is its stack pointer that keeps track of subroutine return addresses. Corrupting the stack pointer by careless programming or by faulty software will crash all systems. The 68000 actually has two stack pointers, one for the operating system and one for all user applications. Whatever a user does, the operating system's own stack pointer cannot be accessed by the user. Therefore, if the user crashes an application, the operating system can step in and gracefully recover.

One of the things I emphasise is the design of robust systems. Whenever you're beginning to think that you must be paranoiac, just remember that the world really is out to get you. If you design a microprocessor system you should try to make it robust and able to handle life's little problems. Once more, the 68000 has facilities that enable it to recover from a wide range of errors. Consider this example. In the early days of the 8-bit microprocessor, programmers had great fun trying out what they called 'undocumented op-codes'. Not all possible binary codes were allocated to the instructions documented in a microprocessor's data sheet. Programmers tried executing these undefined op-codes and, occasionally, they found one that did something useful.

I have nothing against experimentation, but a few programmers actually started using these undocumented instructions in their programs. If you think for a moment, a manufacturer is unlikely to provide useful instructions and then not tell the user! These instructions may not always work. For example, they may fail if preceded by certain other instructions. The manufacturer may change the design of the chip and the undocumented instruction may stop working.

The 68000 checks each instruction as it is executed. If an op-code is not valid, it immediately jumps into its supervisor mode (if it wasn't already in it) and calls upon the operating system to deal with the problem. Illegal instructions are usually encountered when a processor executes a jump to a region of memory containing data rather than instructions. Besides its ability to deal with illegal instructions, the 68000 can recover from problems that would cause many other processors to crash terminally. Error recovery mechanisms exist to deal with division by zero, attempts to read faulty or non-existent memory, and spurious interrupts.

So far we have talked about the software or architecture of the processor. I also teach the design of microprocessor systems. Once again, the 68000 makes a good vehicle for teaching microprocessor interfacing techniques. When teaching bus protocols, I use the 68000's asynchronous bus cycle as an example. The 68000 tells memory that it wants data and then patiently waits until the memory provides it. Should the memory not deliver data within a reasonable time, you can apply a pulse to a special pin to kick it out of its waiting state and force it to take action. This takes us back to the question of robustness.

Development

Up to now I have talked only about the 68000. Since Intel and Motorola have access to the same basic technologies, it is reasonable to expect that developments in these two companies take place in parallel. Over the years Intel produced the 8086, 80286, 80386 and 80486 series and Motorola produced the 68000, 68020, 68030 and 68040. You might be surprised to learn that I don't concentrate heavily on these much more advanced devices, as the basic 68000 illustrates much of what I aim to teach. I will briefly describe the way in which these processors have developed.

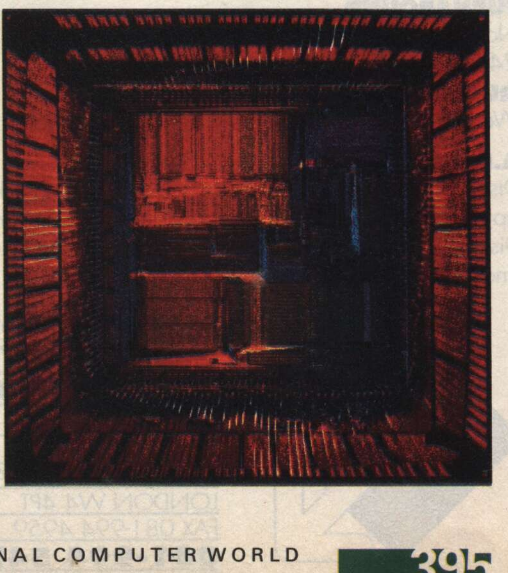
The 68020 is a super-68000 with full 32-bit address and data buses. Improvements in both its internal organisation and design make it much faster than the 68000. As far as the applications programmer is concerned, the 68020 has the same registers as the 68000. It has a few new instructions and some powerful addressing modes that enable it to handle complex data structures. Its most significant feature is its ability to handle bit fields. Unlike other processors the 68020 can move groups of between 1 and 32 bits from place to place irrespective of normal 8-bit boundaries. This feature makes it suitable for image processing or for the handling of data structures on disks.

Time may prove me wrong, but I regard the 68020 as the high point of microprocessor development. Many current developments in microprocessor technology, such as RISC, seem to be aimed at increasing speed or in adding operating system facilities. For example, the 68030 is virtually the same as a 68020 plus a sophisticated management system. This enhancement doesn't speed up the processor's performance or provide the programmer with any useful facilities. Rather, it permits the use of operating systems like Unix, enables you to have virtual memory facilities and to run programs simultaneously with each program protected from corruption by other programs.

When I teach memory systems design, I cover cache memory. A cache is nothing more than a copy of recently accessed data which is kept in a small but fast memory on the chip. When the processor requests data from memory, it is probable that it will find it in the fast cache rather than the slower external memory. Both the 68020 and the 68030 have on-chip caches — the 68020 caches instructions and the 68030 caches both instructions and data. These are quite small caches but they enable me to teach the basic principles.

The 68040 represents a major departure from the 68000 family. It has larger instruction and data caches than the 68030 and two memory management units, one for accesses to data and one for accesses to instructions so it can read an instruction and data simultaneously. It also has an on-chip floating point co-processor.

Computer salespeople often phone and attempt to sell me their systems. They begin by telling me how powerful the computer is. More often than not, I have to patiently explain that I am not interested in what their system does but in how it does it. I use the computer as an aid to teaching and not as an end in itself. Consequently, I shall continue to build my courses around the 68000 family. My only regret is that IBM didn't take the same decision a few years ago.



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MX2448	As MX2400 plus group 3, 2400 – 4800bps send fax facility. Software features: MNP4/5; send high quality text or graphics fax; automatic cover page generation; transmission report Log; company header; fine resolution mode up to 200dpi; phone number management for mail shots.	**£109.00**
ZX2496	9600bps Send/Receive Fax plus 2400bps-4800bps V22bis/22/21 Bell & CCITT Modem. Features include: Send & Receive high quality fax messages in background; View/print received messages; auto detect modem & fax calls; delay transmission for cheap rate calls; comprehensive log report; auto redial; dBase compatible phone database; advanced mail merge; high resolution 200dpi mode; supports multiple printers including 9/24 pin & 150 dpi/300 dpi lasers; multiple file format support; MNP 4/5 communications software with power scripting included.	**£145.00**
ZX2496E	Enhanced ZX2496 version plus V42 & MNP2/3/4/5 hardware error correction.	**£165.00**
1496i	Same spec. as ZX2496 plus 14,400bps modem plus MNP5/V42bis and 14,400 fax.	**£349.00**
2496EP	The portable Fax/Modem. High-Tech, compact professional design. Features: Group 3, send/receive fax; Advanced Laser Jet printer capture; Call scheduled transmission; battery auto sleep mode. V21/22/22bis/Bell 212A/103 plus MNP 2-5 error correction & V42/V.42 bis compression. Error free data throughput up to 9600bps! This is a complete "plug in & go" package, including software, manuals, AC adaptor, PP3 battery & 9/25 pin serial cable. Free compuserve membership pack. Free Winfax version 2 while stocks last!	**£179.00**
WINFAX	Winfax Pro version 2 UK, Including Delrina UK hotline support, available with purchase of Datatech fax modem.	**£45.00**
MXE2400	External MX2400 modem with Status display lights, on/off switch, compatible with any computer RS232 port, MNP4-7 PC Software up to 7200bps	**£109.79**
TX2400	Internal V21/22/22bis dedicated modem for Toshiba laptops. Not T1/2000.	**£109.79**
T3234D	Dedicated Toshiba laptop Modem: T1000/2000/1200/1600/3100/3200 + Software.	**£179.00**
PM2448	Small V21/22/22bis pocket modem plus 4800bps send fax. MNP 4/5 software.	**£109.79**
9600S	V32/22bis/22/23/21/42/42bis MNP 2/5 internal PC high speed modem.	**£299.00**
2400S+	Omnitel V42bis/22bis/22/21/23 & MNP5 external modem. Speeds up to 9600bps.	**£199.00**
WS3000	Miracom Internal or External V22bis/22/21/23 modem including datatalk sw.	**£145.00**
FS100	The advanced fax switch, compatible with answer phones/extension phone.	**£99.00**

Please note the above modems except 2400S+ WS3000 & FS100 are not BABT approved but are designed for international use including the UK. Supplied with free BT or RJII terminated lead.
Please ask for our comprehensive information pack, including our range of "approved" modems.

Prices EXCLUDE VAT. 5 Year warranty on MX/TX/SM/PM/WS/ZX units, 1 year on others.
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